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Temperature Measurements of Shock-Compressed Deuterium

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Abstract

We measured the temperatures of single- and double-shocked D_2 and H_2 up to 85 GPa (0.85 Mbar) and 5200 K. While single shock temperatures, at pressures to 23 GPa, agree well with previous models, the double shock temperatures are as much as 40% lower than predicted. This is believed to be caused by molecular dissociation, and a new model of the hydrogen EOS at extreme conditions has been developed which correctly predicts our observations. These data and model have important implications for programs which use condensed-phase hydrogen in implosion systems.

Temperature measurements of shock compressed materials provide a very sensitive constraint to theoretical models of the equation of state. This is particulary true for those materials in which shock energy can be absorbed in internal degrees of freedom. In the case of liquid nitrogen, shock temperature measurments showed that dissociation resulted in the phenomenon of "shock cooling." [1] In a series of recent experiments, we measured the temperatures of shock-compressed D_2 and H_2, and the results have led to a revision in models of hydrogen at high pressure and temperature.

We performed single and double-shock experiments, in which we measured the temperature during the passage of a strong shock in the fluid, and after reflection of the shock off a transparent window. Most of the measurements were in (initially liquid) D_2, since its use allows higher pressures and temperatures to be obtained than with H_2. Details of the experimental setup can be found in Refs. 2 (D_2 EOS and cryogenic methods) and 3 (optical pyrometer), and the details of this work, its analysis, and the new theoretical model are found in Ref. 4.

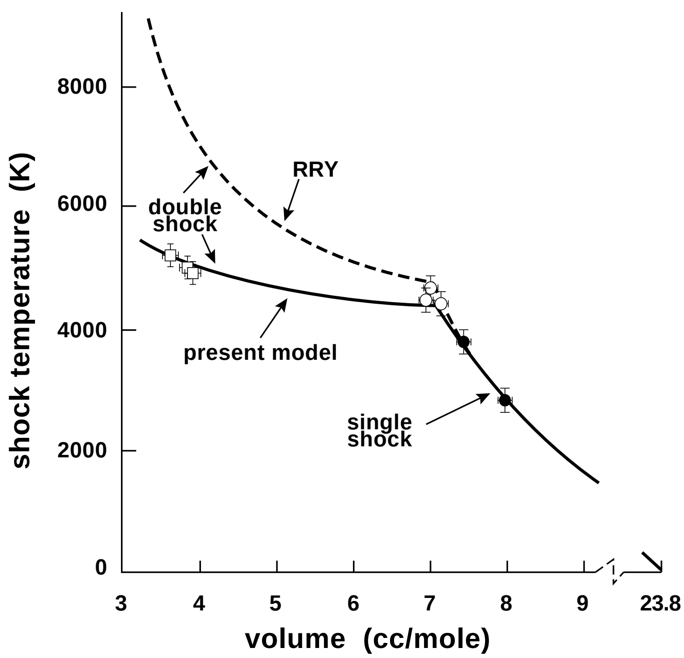

Fig. 1. Comparison of previous theoretical model for D_2 by Ross, Ree, and Young [5], denoted by RRY, with the present model. Circles refer to single shock states, squares to double shocks. The sets of open circles and open squares are for pairs of single and double shock measurements.

The large two-stage light-gas gun in B. 341 was used to generate the shock waves, using projectile velocities up to 7.2 km/s. The hydrogen samples were condensed from research-grade gas into a sample cavity 1.5 mm thick surrounded by liquid H_2 at 20 K.[2] The experiments were planar and one-dimensional in the observation region. We observed the shock temperatures using a fiber-optic-coupled optical pyrometer with an effective sensitivity of f/2.5 and 1 ns time resolution.[3] The sample cavity was bounded on the impact side by an Al plate, on the other by transparent Al_2O_3 or LiF windows. These windows remain transparent under the conditions of shock loading in our experiments. The results of our experiments on D_2 are plotted in in Fig. 1.

The new model developed by Ross,[4] indicated in the figure as the “present model,” assumes that the properties of the shocked fluid can be accurately expressed as a mixture of pure phases: molecular and monatomic hydrogen. This model leads to a thermodynamically self-consistent effective density- and temperature-dependent dissociation energy for calculating the fraction of dissociated molecules. Since the value of this dissociation energy decreases as the the hydrogen is compressed, we predict that hydrogen undergoes a continuous dissociative phase transition in the region of our experiments. The agreement between calculated and measured temperatures, shown in Fig. 1, is remarkably good. This provides us with confidence in the predictive ability of our model. In Figure 2, we compare the principal Hugoniot calculated with the present model (solid line), the old (RRY) model,[5] and to various tabular

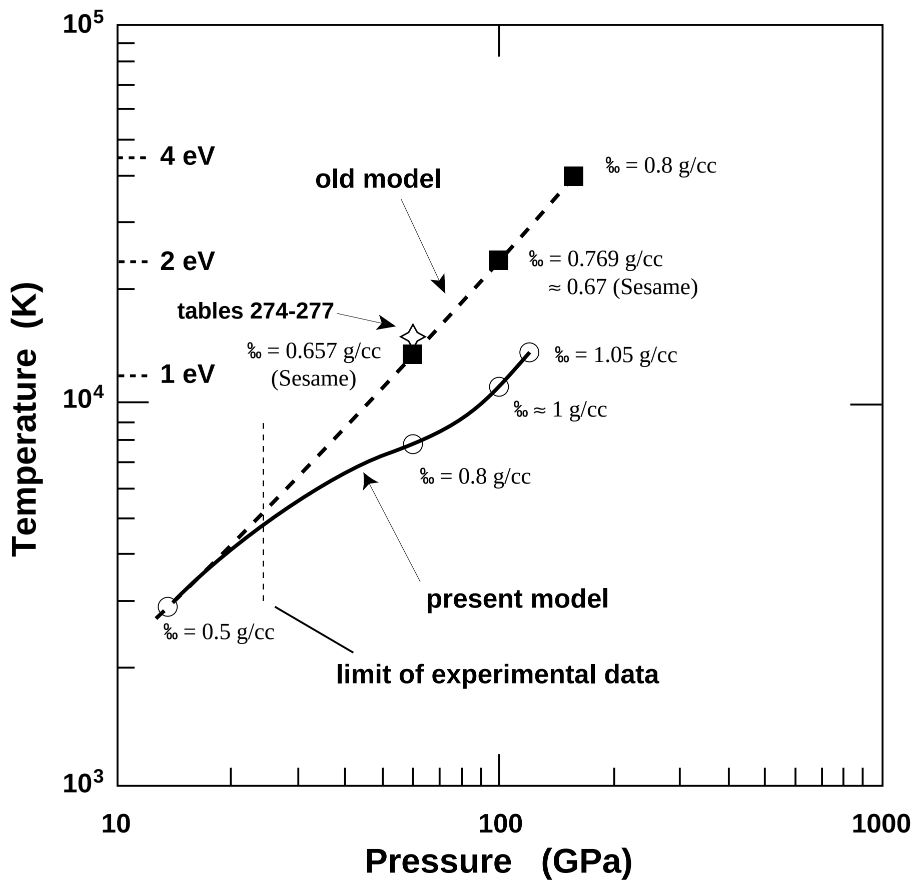

Fig. 2. A calculation of the temperature along the principal Hugoniot of liquid D_2 as a function of pressure with the present model (solid curve), with the old model (dashed curve), and tabular equations of state . Representative densities along each locus of states are indicated by open circles and squares for the present and old models, respectively.

equations-of-state now in use. The tabular data is essentially the same as the old model. On the Hugoniot, we can expect more compression and lower temperatures than previously believed. This is good news!

It is clear from Figure 2 that these calculations are a significant extrapolation beyond our current data set. Higher initial pressures are possible using our gun, up to nearly 30 GPa single shock, 140 GPa in double shocks. We plan to perform experiments to measure the single- and double-shock EOS, and then the shock temperatures at this pressure in the future, to further test and refine the present model.

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